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ABSTRACT. The history of automatic control in Russia is reviewed. This includes: temperature control, launch vehicles, communication satellites, weather satellites, planetary satellites, lunar satellites, manned flights.

The ten years that have passed since the day the first arti- /ll ficial celestial body was launched into space, the day opening a new era in the history of the subjugation of nature, have been marked by the vigorous growth of rocket-space engineering. It is impossible to name another branch of engineering in which, during the past ten years, such impressive progress has been achieved. The technical potential accumulated over many years, in fields which it would appear were only slightly connected with this area, led to the fact that in 1957 it became possible to achieve one of the boldest ideas of mankind.

The first scientific work devoted to man's mastery of outer space appeared in Russia at the beginning of this century in the works of the great Tsiolkovskiy. These works, which are now generally well known, as well as the works of his successors initially were of a purely theoretical character. It was only in the 1920's and 1930's that work on rockets and rocket engineering stopped being the privilege of theoreticians and populizers, and became the subject of systematic activity of scientists and en-

[&]quot;Numbers in the margin indicate pagination in the foreign text.

gineers of the appropriate scientific research institutes and design organizations. The successes achieved in the prewar years were consolidated and augmented by the work of the 40's and 50's which expanded very broadly in the Soviet Union. The academician S. P. Korolev was a prominent scientist in the field of rocket engineering and was one of the organizers of this work. Korolev began his fruitful investigations more than 35 years ago. Large groups of scientists and designers, without whose creative contribution the success of the entire undertaking would have been impossible, worked at the same time as S. P. Korolev on this problem.

Let us remember that, in order to create the powerful rocketspace complexes, it was necessary to solve problems which presented
formidable difficulties: to create gigantic ultralight rocket designs, large liquid-fuel rocket engines and a complex assembly of
ground-level equipment; to develop designs for satellites and interplanetary equipment which were capable of prolonged operation
in the specific conditions of outer space; to ensure the heat
shielding of space equipment with its entry into the Earth's atmosphere at cosmic velocities, and, for piloted satellites, to solve
a series of problems of a medical-biological character. This list
could be expanded considerably; however, let us limit ourselves to
only a brief investigation of those problems which are connected
with automatic control.

One may list here the problem of creating automated stabilization of a rocket-carrier. This not only ensures angular stabilization, the maintenance of a given ascent trajectory and the switching-off of the rocket engine at the necessary moment, but also /12 limits the elastic vibrations of the rocket's body and the surges of the liquid masses in its tanks. This problem also is of importance for space equipment (for example, under the conditions

of correcting the flight trajectory for a soft landing on the Moon). However, along with this, new problems also arise, such as the creation of systems for the orientation of space equipment which are capable of continuous operation for many months, the development of on-board equipment complexes which automatically switch on and switch off the necessary instruments, the creation of systems for automatically maintaining a given temperature, etc.

Only large teams of scientists are able, on the basis of theoretical, experimental and test design work, to find the correct answer to all the problems which arise.

Summing up the last decade, let us dwell mainly on the questions of automatic control in outer space.

It is more convenient to conduct an investigation of this aspect of the development of rocket-space engineering by dividing all space equipment into several groups, combining in them the designs which have approximately the same purpose. If one follows such a principle, then all the space equipment which has been created may be conveniently divided into the following groups: artificial satellites of the Earth (among them satellites of importance to the national economy); automatic equipment for investigating the Moon and the space around the Moon; automatic interplanetary stations for flights to the orbits of Mars and Venus and, finally, manned spacecrafts.

The world's first artificial satellite of the Earth was placed into orbit by the Soviet Union on October 4, 1957. This marked the beginning of the systematic investigation of outer space, and opened the prospects for mankind to go out into interplanetary space. Following this, a large number of satellites of the most diverse type were launched. These satellites gave abundant information for expanding and refining our concepts of

near-Earth space.

If the first satellite was structurally simple and its launching was done mainly for the purposes of test firing the rocketcarrier and obtaining the very first data from outer space (a study of the transmission of radio waves, determining the density of the upper atmosphere, etc.), then subsequent satellites were equipped with more refined equipment and more complicated problems were formulated for them. This led to the appearance of automatic control systems of a very diverse character and many ramifications. final result, a functional circuit of the following type became typical for the interval of time being investigated. A central switching-logic instrument mounted on board provided automatic control for all the main systems of the spacecraft equipment. connected with the systems we have talked about and, in particular, with the command radio link. All communications with the ground control points are accomplished along this link, and signals confirming the execution of received commands and data on the state of on-board systems and the operations being conducted on board are transmitted to the Earth along the link. The central instrument converts the commands received by radio in the proper way, switching on or switching off appropriate systems and performing the necessary logic operations, thereby coordinating the operation of the various space equipment systems. Among the main systems one may list, for example, the propulsion system, the power supply system, the scientific equipment, the temperature regulation system, etc.

The collection of systems described here is a typical example of nonautomatic control. At the same time, it is clear that it is impossible to supply from the Earth the entire set of necessary commands if one assumes that every switching on board may be achieved only in this way. For example, suppose a certain drive

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exists which, by turning in one direction or another, may change the temperature conditions of the space equipment. It is obvious that it is necessary to rotate it, not by sending a command from the Earth, but on the basis of signals from a temperature sensor which has been included in the appropriate automatic regulation circuit. In this case, the central instrument only maintains the function of switching on or switching off the temperature regulating system in accordance with the command arriving by radio.

In other cases, in order to have correct functioning of the equipment, it is necessary to perform not a single switching on, but a whole series of such switchings according to a rigid time Suppose it is necessary to slow down a satellite before landing, and switching on the rocket motor is connected with this. Then a series of necessary commands (switchings) could appear as follows: the delivery of power to the stabilization system for a certain interval of time which is necessary for undoing the gyroscopes, the delivery of an unlocking signal to them, then a series of successive switchings which is connected with preparing the rocket engine for firing, etc. Therefore, an instrument connected with the central instrument must exist on board a spacecraft which stores the entire necessary set of such time programs. also simultaneously perform the functions of an on-board time keeper. Such a device is called a time program device. Sometimes its functions are expanded, and it may set the program for the entire flight. In this case, the necessity for supplying commands from the Earth is theoretically eliminated and the entire control becomes automatic. In practice, both automatic control and also control on the basis of commands from the Earth are usually used. These systems duplicate one another where this is useful, and they attempt to make the most rational distribution of the problems between them.

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Regarding the scientific equipment, its connection with the central switching-logic instrument and other systems of the satellite has a slightly different character. In the final analysis, the main purpose of launching a satellite is to obtain scientific data; therefore, all systems mounted on board may be regarded as devices servicing the scientific equipment.

This explains the fact that the specific weight of one or another of the on-board systems on the whole is determined by the scope of scientific problems confronting the satellite. In certain cases, the collection of on-board automatic control systems for the satellite drops into second place in comparison with the scientific equipment. Soviet satellites of the series "Proton" are a characteristic example of such equipment. These satellites which weigh 12.2 tons are in essence flying instruments for the space study of superhigh energy cosmic particles by direct methods. It is self-evident that in this case the scientific equipment contains a number of devices operating on the automatic control principle.

Ten-year studies of interplanetary space have given, as is known, many new and sometimes unexpected results. New directions in science and new points of view have appeared. However, one should be surprised to discover the fact that during this short period of time artificial satellites of the Earth also have begun to be used for national economic needs. Here, first of all, it is necessary to mention their use for communications and in the weather service. Satellites of the "Molniya" series, which have been systematically launched in the Soviet Union since the beginning of 1965, have enabled us to connect the eastern and western regions of the country with two-way multichannel telephone, phototelegraphic, and telegraphic communications. In addition to this, the transmission of television programs was accomplished

from Moscow to Vladivostok and in the reverse direction (a distance of 6,500 km). Also experimental transmissions of colored television were produced between Moscow and Paris. In all these cases, the communications satellite "Molyniya" operated as an automatic radio relay.

In addition to the things we have talked about, television <a href="Likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelites-likelite

Special meteorological satellites which are components in the "Meteor" system give considerably more complete and valuable information for the weather service. Not only images of the cloud and snow cover, but also data recorded by actinometric equipment are transmitted to the Earth from the satellites of this system.

In the control systems for automatic satellites of the "Molni-ya" and "Meteor" classes, pasically the same functional circuit is used as was described above. The sole difference, perhaps, is the absence (or sharp reduction in number) of scientific equipment and the replacement of it by radio relay equipment in the communications satellites and by meteorological equipment in the satellites of the "Meteor" system. This may impose additional requirements on the automatic control systems which are mounted on board the satellites. Let us illustrate this with an example. As is known, the satellite "Molniya" travels along a highly elongated elliptical orbit with an apogee of the order of 40,000 km, and it is orientated at all times with its axis of symmetry towards the Sun (this also is maintained when the satellite briefly passes through the

Earth's shadow). Such an orientation is connected with the necessity for the constant replenishment of electric power reserves which come from solar batteries. It is easy to see that in this case the angle between the direction to the Sun (and this means also the satellite's symmetry axis) and the direction to the Earth will change in accordance with its motion along the orbit, and the pencil-beam parabolic antenna mounted on the satellite must change its position with respect to the satellite's body. In order to achieve a homing of the antenna on the Earth, the antenna is equipped with an optical device which responds to light from the Earth and is included in the circuit for automatically controlling the antenna position. Thus, in addition to the system for orienting the entire satellite as a whole, there is a device for tracking some external reference point on board the satellite.

Systematic work in studying the celestial bodies closest to us - that is, the Moon, Venus and Mars - was conducted during the past ten years in the Soviet Union simultaneously with the study of near-Earth cosmic space. The automatic interplanetary stations of the series "Luna," "Zond," "Venera" and "Mars" which were created for this purpose differ very substantially from the artificial satellites of the Earth, even if we limit ourselves to an investigation of only the single question of automatic control. This difference appears mainly in the propulsion control system. Whereas the artificial satellites of the Earth (which should not be turned to the Earth) sometimes may be generally stripped of the propulsion control system, on equipment designed for flights to the nearest celestial bodies these systems become the systems which are mostly responsible for determining the success of the entire undertaking. This is connected with the fact that flights to such great distances are unthinkable without correction of the trajectory during the flight. This correcting maneuver must be performed with high precision and this requires the orientation

of the space equipment to a direction known beforehand with an error rarely exceeding minutes of angular measure. In addition to this, the problems of radio communications with space equipment which is at a distance of tens and hundreds of millions of kilometers from the Earth also have their own specific characteristics. All this, plus certain other distinctive features of the space equipment being investigated, led to the development of multifunctional automatic propulsion control systems for them. These systems are capable of solving the diverse problems which \(\frac{15}{25} \) arise with changes in the flight procedures. For automatic interplanetary stations of the series "Zond," "Venera" and "Mars," the following procedures are characteristic:

- 1) Prolonged orientation of the working surfaces of the solar batteries toward the Sun;
- 2) Precise orientation with respect to celestial reference points before correcting the trajectory;
- 3) Orientation of the parabolic antenna toward the Earth in order to establish high-information communications;
- 4) Stabilization when the correcting rocket engine is operating.

The first of the above listed procedures is realized by using a special optical sensor for orientation toward the Sun. This sensor is connected with a logic circuit enabling the circuit to generate the necessary control signals without obtaining information concerning the angular velocity of the space equipment. The procedure is characterized by a low orientation precision $\pm 10^{\circ}$) which is sufficient for normal operation of the solar batteries and by an extremely high economy (a compressed nitrogen consumption of around 300 gf per month and an average electric

power consumption of 2.5 watts).

The precise orientation procedure before corrections required the development of a complex optical-electronic sensor which was capable of generating signals showing deviation from the reference points (the Sun and Canopus were selected as the reference points) by angles on the order of minutes. It is obvious that the position of the sighting axes to the Sun and to the star Canopus with respect to the body of the space station may be transmitted to the station along the command radio link only after determining the actual flight trajectory. In this precise orientation procedure, both the optical sensor signals and also signals from the angular velocity gyroscopic sensors are used.

The procedure for the orientation of the parabolic antenna toward the Earth is also accomplished according to a similar scheme, with the only difference being that the Sun and Earth were selected as the reference points. The corresponding angles between the lines of sight and the space equipment are determined automatically without using the command radio link, since the flight trajectory is known beforehand with the necessary precision.

The procedure for the orientation system may be given by an appropriate command from the Earth. Switching on the communications using the parabolic antenna or the orientation with respect to the Sun and Canopus before correcting the trajectory involves rotation of the space equipment, and therefore may lead to a temporary cessation of the orientation of the solar batteries toward the Sun. If one considers that the communication sessions may be repeated fairly frequently, then it becomes understandable that great attention is alloted to problems of the reliable transition from one procedure to another. In particular, the logic of the operation of the orientation system is constructed in such

a way that every switching procedure is automatically terminated when changing to the procedure for orienting the solar batteries toward the Sun.

The stabilization procedure when the rocket engine is in operation is slightly different from that characteristic for the rocket-carrier. Here a complex of free gyroscopes, angular velocity sensors, and indicators of the lateral velocity component which are being created by the rocket engine is used. The rocket engine is switched on by means of a signal from the gyroscopic integrator of longitudinal accelerations. As is seen from this brief characterization, the stabilization system has a traditional character. Soviet engineers have many years of experience in the creation of such systems, since the first gyroscopic systems for rocket stabilization were created and subjected to flight tests in the USSR more than 30 years ago.

The entire assembly of the propulsion control system for long-range space equipment has reached a high degree of refinement. In this connection, it is helpful to recall certain data from the flight of "Venera-3." During the flight. 31 communication sessions were conducted (16 of them before the trajectory correction) during which more than 1,300 range measurements to the station were made, and more than 5,000 measurements of the radial component of the flight velocity and around 7,000 measurements of the angular coordinates were performed. All of this enabled us to conduct a continuous and very precise observation of the actual flight trajectory. The measurements showed that, as was expected, despite the good initial takeoff of the automatic station on the flight trajectory towards Venus, the miss in the vicinity of the planet for which it was headed would be 60,550 km from its center which exceeds by approximately a factor of five the planet's diameter. In order to change to a flight trajectory which would strike the target, a correction to the

motion was made by firing (with the proper orientation) the rocket engine. This was done when the station was at a distance of 12,900,000 km from the Earth. The trajectory measurements which were made after the correction was carried out showed that the necessary flight velocity was obtained with a precision of several centimeters per second. After the correction, the flight trajectory passed at a distance of 450 km from the center of the planet. Even if one considers the errors in determining the trajectory (less than 600 km) and the inaccurate knowledge of the astronomical constant for the solar system which gives, for this flight, an additional error of less than 500 km, the mean square deviation from the calculated trajectory is no more than 800 km. If, furthermore, one takes the fact into account that it appears as if the corridor of trajectories with its approach to the planet is contracted by the planet's pull of gravity (for this flight it decreased to approximately one half) and that the radius of Venus is 6,100 km, we arrive at the conclusion that there is a 10 - 15 fold margin of accuracy for hitting the planet on this flight.

In addition to everything else, this flight is remarkable in that it delivered the first load to a planet of the solar system.

A systematic study of the Moon by means of rockets was begun in the Soviet Union in 1959. It would be appropriate to dwell here for a moment on two works which represent a stage in the developing program.

October 4, 1959, which was exactly two years after the launching of the first artificial satellite of the Earth, marks the date of the automatic interplanetary station "Luna-3" which was the first space device equipped with an orientation system. Such a system was necessary, since the automatic station was designed

for photographing the back side of the Moon. As is known, this experiment was successfully completed. The orientation system used on the automatic interplanetary station "Luna-3" was relatively simple. It consisted of two groups of optical sensors (solar and lunar), gyroscopic sensors of the angular velocity, a logic unit and a system of jet engines operating on compressed nitrogen — that is, it contained all the main elements of orientation systems. The control of this system, the photographic equipment, the television, and other devices, was accomplished both from the command radio link and also from the on-board automatic equipment which included time program devices.

This and other automatic stations similar to it were able to give only partial scientific information concerning the Moon, whereas the other part of the data could only be obtained by instruments achieving a soft landing on the Moon's surface. fore, several years after the successful flight of the automatic station "Luna-3" they began in the Soviet Union to finish the work for a soft landing of space equipment on the Moon's surface. This work was successfully completed on February 3, 1966, with the descent onto the lunar soil of the automatic station "Luna-9." Space equipment of this type used a propulsion control system containing a system for orientation with respect to the Sun, Earth, and Moon which enables a trajectory correction to be made. space equipment also uses a system for stabilizing the angular position during the operation of the correcting engine. Although these systems differ structurally from the ones which were described above, they resemble them a great deal, since they perform very similar functions. In the system being studied, the equipment for the soft landing on the Moon's surface was new in princi-It turned out to be necessary to make measurements of the distance from the lunar surface during the flight, to switch on the descent engine in order to reduce the approach velocity to the

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Moon, all the time maintaining the required position of the space equipment with respect to the local lunar vertical, etc. The successful solution of the new combined problems must be recognized as one of the greatest engineering achievements.

If one glances over the path that has been followed these last ten years it is difficult to overestimate what has been achieved in such a short period. The mastery of outer space by man required the creation of automatic space equipment. Many achievements of automatic control engineering were used in this equipment. engineering achievements provided brilliant examples for engineering solutions in this fruitfully developing field. However, the main purpose of all these space efforts was not so much to obtain new scientific data, as to outline that path along which mankind must travel. Here the development of engineering followed a path opposite the usual one. Up to this time, even in such a young field as aviation, everything new was investigated by men, and only later and gradually did automatic control arrive in these fields mastered by men. In the field of space engineering, automatic control laid and is laying the paths along which man must travel.

Man dared for the first time to go out into outer space on April 12, 1961, when Yuri Gagarin accomplished his flight in the spacecraft "Vostok." In all its main parameters, this spacecraft must be referred to as automatically controlled. Although manual control systems also were mounted on board, they were used to a minimum degree. Regarding the automatic systems, they were made according to the most simple and reliable schemes. In subsequent flights on spacecrafts of the series "Vostok" and "Voskhod," the crew's participation in the spacecraft control gradually increased, and simultaneously the functions which were entrusted to the cosmonauts became more complicated. Scientists (K. P. Feoktistov,

B. B. Yegorov) began to conduct investigations in outer space and the cosmonaut A. A. Leonov, who in March, 1965, left the spacecraft to walk in outer space, showed that man was able to work in outer space under the most difficult conditions.

The attraction of cosmonauts to the active control of spacecrafts again emphasized the importance of studying the interaction of man and machine. A great deal of this study coincided with the problems which had already arisen and were being studied in aviation, but problems inherent only to astronautics also appeared. Here we do not need to talk about the effect of weightlessness and other similar factors on the working efficiency of man. are being studied in space biology. Even if we stay away from these factors, we can point to a number of specific features which sharply distinguish the techniques for manually controlling spacecraft from similar problems for controlling an aircraft.

One may, for example, point to the fact that a pilot when controlling an aircraft accomplishes the necessary evolutions by appropriate turns of the aircraft around its center of mass in respect to three axes. As is known, not only does the angular position of the aircraft in respect to fixed reference points change, but also a change in the flight trajectory takes place, since the equations of motion for the aircraft as a material point contain terms which depend on its angular position in respect to the velocity vector and the fixed coordinate system. Saying it another way, the pilot changes the flight trajectory by changing the angular coordinates of the aircraft. For spacecraft the equations of motion for the center of mass and the motion around the center of mass, as a rule, are independent, and the control problem which is presented to the cosmonaut has six independent coordinates instead of the three coordinates in aviation.

Furthermore, in aviation the problem of prompt reaction to a rapidly changing environment plays a very big role. In certain astronautics problems, this problem maintains its importance (a controlled descent in the atmosphere, landing on the Moon, etc.). However, in many cases, because of the very small angular velocities which the spacecraft develops, engineering psychology encounters the problem of an excess time and not a shortage of time.

The development of astronautics has already led to the fact that automatic control systems have appeared which have been especially adapted to operate in outer space conditions. We are speaking about operation in weightlessness, in a vacuum, with difficult heat conditions, etc. The space conditions turn out to have more than a complicating influence on the operation of the equipment being developed. Judicial use of the properties of outer space and the peculiarities of the dynamics of motion of space equipment in outer space lead to new instrumental solutions which are unknown in everyday practice here on Earth. Thus, in addition to free gyroscopes, gyro platforms, angular velocity sensors and other similar devices used in aviation and on ships, devices have appeared which can only be used in space. Let us refer, for example, to a gyro-orbit — a gyroscopic instrument which is able to locate the trajectory plane under the condition that the local vertical on an artificial satellite of a planet already has been constructed; an infrared local vertical synthesizer; a flight velocity direction sensor which uses the presence of ions in the upper atmosphere, etc. The examples which have been presented show that mastery of outer space by man must be, and will be, accompanied by using the properties of space which are useful when solving certain of the problems.

The development of automatic control systems for space equipment was conducted and is being conducted on the basis of classical automatic control theory. However, it is interesting to note that in this field we also have been obliged to develop new branches of theory. Even in regards to such a problem as the investigation of two-dimensional vibrations which had been studied in detail, they have succeeded in finding new and unexpected results. Thus, for example, it turns out that the consumption of the working medium by the orientation engines is quantized, and changes abruptly with a continuous increase of the external moment acting on the space equipment. A more thorough investigation of this problem led to the necessity of working out new problems in the theory of point transformations.

The examples which have been presented show that the creation of the means for automatic control in outer space is not only associated with the use of instruments and theoretical solutions which are already known, but it, in turn, enriches both theory and also engineering practice.

Finally, the vast resources needed for carrying out the space programs are not expended for only this sake. Probably, obtaining scientific results connected with the possibility of directly studying outer space do not fully justify the expenses.

All this sometimes gives rise to critical remarks, and some prominent scientists consider the resources expended to be too high a price for mankind to pay for the scientific results which are being obtained. The efforts being expended are justified by something else. We live in an era similar to the era of the great geographic discoveries, and it is necessary to treat the mastery of outer space not only as conducting certain scientific experiments, but also as broadening the sphere of human endeavor.

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